

# Effects of elastic and inelastic $NN$ scattering cross sections on $\pi^-/\pi^+$ ratios in heavy-ion collisions at intermediate energies

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Based on the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model and the scaling model according to nucleon effective mass, effects of elastic and inelastic  $NN$  scattering cross sections on  $\pi^-/\pi^+$  in the neutron-rich reaction of  $^{48}\text{Ca}+^{48}\text{Ca}$  at a beam energy of 400 MeV/nucleon are studied. It is found that cross-section effects of both  $NN$  elastic and inelastic scatterings affect  $\Delta_{1232}$ ,  $\pi^-$  and  $\pi^+$  production, as well as the value of  $\pi^-/\pi^+$ .

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Recently, pion production in heavy-ion collisions has attracted much attention in the nuclear physics community [1–5]. One important reason for this is that pion production is connected with the high-density behavior of nuclear symmetry energy [6]. The latter is crucial for understanding many interesting issues in both nuclear physics and astrophysics [7–13]. The high-density behavior of nuclear symmetry energy, however, has been regarded as the most uncertain property of dense neutron-rich nuclear matter [14, 15]. Many microscopic and/or phenomenological many-body theories using various interactions [16, 17] predict that the symmetry energy increases continuously at all densities. However, other models [7, 18–30] predict that the symmetry energy first increases to a maximum and then may start decreasing at certain suprasaturation densities. Thus, currently the theoretical predictions on the symmetry energy at suprasaturation densities are extremely diverse. To make further progress in determining the symmetry energy at suprasaturation densities, what is most critically needed is some guidance from dialogues between experiments and transport models, which have been done extensively in the studies of nuclear symmetry energy at low densities [31–35].

Using  $\pi^-/\pi^+$  to probe the high-density behavior of nuclear symmetry energy has evident advantage within both the  $\Delta$  resonance model and the statistical model [36, 37]. Several hadronic transport models have quantitatively shown that  $\pi^-/\pi^+$  ratio is indeed sensitive to the symmetry energy [5, 6, 38, 39], especially around pion production threshold. These transport models, however, usually use different elastic and inelastic  $NN$  scattering cross sections. For the in-medium  $NN$  elastic scattering cross section, different transport models use different forms. For the  $NN$  inelastic scattering cross section, they usually use free  $NN$  inelastic scattering cross section. The in-medium  $NN$  inelastic scattering cross section must be different from that in free space, and currently the in-medium  $NN$  inelastic scattering cross section is quite controversial [40–44]. More importantly, the description of meson production in heavy-ion collisions is still a very open problem. Other effects, apart from the one considered here, may change the  $\pi^-/\pi^+$  ratio. For instance, in Ref. [3], the authors discuss in-medium

effects, owing to the interaction of pions with nucleons, on the charged-pion ratio, which go in the direction of reducing  $\pi^-/\pi^+$  ratio. However, the cross-section reduction effects investigated in the following increase the charged-pion ratio. All these effects on pion production are combined with the effects of the isovector part of the nuclear interaction (the symmetry energy), which influences strongly also the isotopic content of pre-equilibrium nucleon emission, changing the asymmetry of the remaining interacting system. From this point of view, it is not so easy to extract information on the high-density behavior of the symmetry energy just looking at pion production and charged-pion ratio, because several effects cooperate to build the final result. All the preceding may cause different translations from experimental data [41, 42, 45, 46]. Here we just study the effects of both elastic and inelastic  $NN$  scattering cross sections on pion production, as well as the value of  $\pi^-/\pi^+$  in neutron-rich heavy-ion collisions because the National Superconducting Cyclotron Laboratory at Michigan State University, Rikagaku Kenkyusho (RIKEN, The Institute of Physical and Chemical Research) of Japan, and the Cooler Storage Ring in Lanzhou, China, are planning to do experiments of pion production to study the high-density behavior of nuclear symmetry energy. In the framework of the isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model, as an example, we studied the effects of both elastic and inelastic  $NN$  scattering cross sections on  $\pi^-/\pi^+$  in the neutron-rich reaction of  $^{48}\text{Ca}+^{48}\text{Ca}$  at a beam energy of 400 MeV/nucleon. It is found that cross-section effects of both  $NN$  elastic and inelastic scatterings affect  $\Delta_{1232}$ ,  $\pi^-$  and  $\pi^+$  production, as well as the value of  $\pi^-/\pi^+$ .

The isospin and momentum-dependent mean-field potential used in the present work is [47]

$$\begin{aligned}
 U(\rho, \delta, \mathbf{p}, \tau) = & A_u(x) \frac{\rho_{\tau'}}{\rho_0} + A_l(x) \frac{\rho_{\tau}}{\rho_0} \\
 & + B \left( \frac{\rho}{\rho_0} \right)^{\sigma} (1 - x\delta^2) - 8x\tau \frac{B}{\sigma + 1} \frac{\rho^{\sigma-1}}{\rho_0^{\sigma}} \delta \rho_{\tau'} \\
 & + \sum_{t=\tau, \tau'} \frac{2C_{\tau, t}}{\rho_0} \int d^3\mathbf{p}' \frac{f_t(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p} - \mathbf{p}')^2 / \Lambda^2}, \quad (1)
 \end{aligned}$$

where  $\rho_n$  and  $\rho_p$  denote neutron ( $\tau = 1/2$ ) and proton

( $\tau = -1/2$ ) densities, respectively.  $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$  is the isospin asymmetry of nuclear medium. All parameters in the preceding equation can be found in refs. [48]. The variable  $x$  is introduced to mimic different forms of the symmetry energy predicted by various many-body theories without changing any property of symmetric nuclear matter and the value of symmetry energy at normal density  $\rho_0$ . In this article we let the variable  $x$  be 1. With these choices the symmetry energy obtained from the preceding single-particle potential is consistent with the Hartree-Fock prediction using the original Gogny force [47] and is also favored by recent studies based on FOPI experimental data [1]. The main reaction channels related to pion production and absorption are

$$\begin{aligned} NN &\longrightarrow NN, \\ NR &\longrightarrow NR, \\ NN &\longleftrightarrow NR, \\ R &\longleftrightarrow N\pi, \end{aligned} \quad (2)$$

where  $R$  denotes  $\Delta$  or  $N^*$  resonances. In the present work, we use the isospin-dependent in-medium reduced  $NN$  elastic scattering cross section from the scaling model according to nucleon effective mass [45, 49–51] and compare with the case of  $NN$  elastic cross section in free space to study the effect of elastic  $NN$  scattering cross section on pion production. Assuming in-medium  $NN$  scattering transition matrix is the same as that in vacuum [50], the elastic  $NN$  scattering cross section in medium  $\sigma_{NN}^{medium}$  is reduced compared with their free-space value  $\sigma_{NN}^{free}$  by a factor of

$$\begin{aligned} R_{medium}(\rho, \delta, \mathbf{p}) &\equiv \sigma_{NNelastic}^{medium} / \sigma_{NNelastic}^{free} \\ &= (\mu_{NN}^* / \mu_{NN})^2. \end{aligned} \quad (3)$$

where  $\mu_{NN}$  and  $\mu_{NN}^*$  are the reduced masses of the colliding nucleon pair in free space and medium, respectively. For in-medium  $NN$  inelastic scattering cross section, even assuming in-medium  $NN \rightarrow NR$  scattering transition matrix is the same as that in vacuum, the density of final states  $D_f$  [50] of  $NR$  is very hard to calculate owing to the fact that the resonance's potential in matter is presently unknown. Because the purpose of present work is just study the effect of  $NN$  scattering cross section on pion production and charged-pion ratio, to simplify the question, for the  $NN$  inelastic scattering cross section we use the same correction factor  $R_{medium}(\rho, \delta, \mathbf{p})$  to study the effect of  $NN$  inelastic scattering cross sections on pion production and charged-pion ratio (i.e., one choice is  $R_{medium}(\rho, \delta, \mathbf{p}) * \sigma_{NNinelastic}^{free}$ , the other choice is  $\sigma_{NNinelastic}^{free}$ ). The effective mass of nucleon in isospin asymmetric nuclear matter is

$$\frac{m_\tau^*}{m_\tau} = \left\{ 1 + \frac{m_\tau}{p} \frac{dU_\tau}{dp} \right\}^{-1}. \quad (4)$$

From the definition and Eq. (1), we can see that the effective mass depends not only on density and asymmetry of

medium but also the momentum of nucleon. We decide  $NR \rightarrow NN$  inelastic scattering cross section according to the detailed balance principle [42]. The reduction factor  $R_{medium}$  thus affects not only pion production but also pion absorption. Shown in Fig. 1 is the reduction

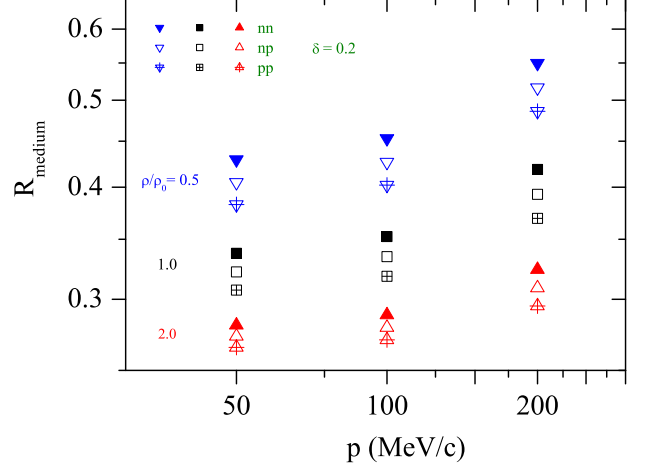


FIG. 1: The reduction factor  $R_{medium}$  as a function of density (0.5, 1.0, and 2.0 times normal nuclear matter density  $\rho_0$ ) and momentum (50, 100 and 200 MeV/c) for  $nn$  (neutron-neutron),  $np$  (neutron-proton), and  $pp$  (proton-proton) colliding nucleon pairs. The asymmetry of nuclear matter is set to be  $\delta = 0.2$ .

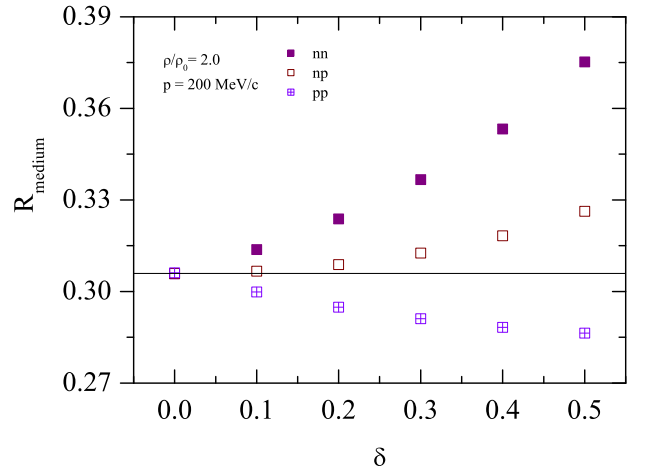


FIG. 2: The reduction factor  $R_{medium}$  as a function of asymmetry  $\delta$  of medium for  $nn$ ,  $np$ , and  $pp$  colliding nucleon pairs. The density of medium is  $\rho/\rho_0 = 2.0$  and nucleonic momentum is  $p = 200 \text{ MeV}/c$ .

factor  $R_{medium}$  as a function of density and momentum for  $nn$  (neutron-neutron),  $np$  (neutron-proton), and  $pp$

(proton-proton) colliding nucleon pairs. We can see that the reduction factor decreases with density and increases with momentum. Also, we can clearly see that the  $nn$  pair's reduction factor is always larger than that of the  $pp$  pair in neutron-rich nuclear matter. Fig. 2 shows the reduction factor  $R_{medium}$  as a function of the asymmetry  $\delta$  of the medium. It is seen that the reduction factor  $R_{medium}$  of the  $nn$  colliding nucleon pair increases rapidly with asymmetry  $\delta$  and the reduction factor  $R_{medium}$  of the  $np$  colliding nucleon pair increases slowly with asymmetry  $\delta$ , whereas the reduction factor  $R_{medium}$  of the  $pp$  colliding nucleon pair decreases slowly with asymmetry  $\delta$ . In the symmetric nuclear matter ( $\delta=0$ ), however, the reduction factor  $R_{medium}$  for the three cases does not split.

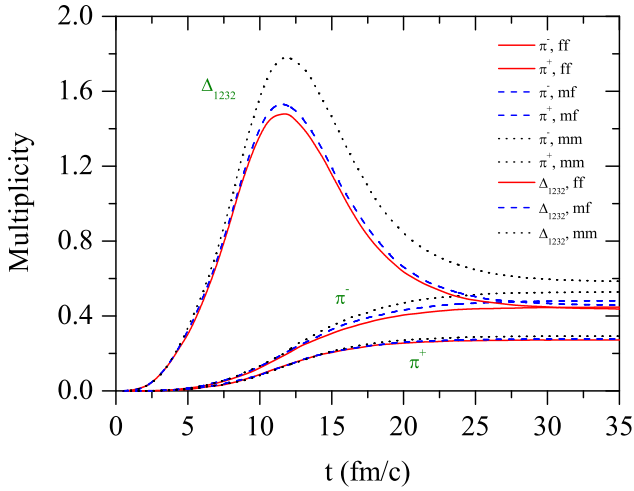


FIG. 3: Evolution of  $\pi^-$ ,  $\pi^+$  and  $\Delta(1232)$  multiplicities in the reaction of  $^{48}\text{Ca}+^{48}\text{Ca}$  at a beam energy of 400 MeV/nucleon. The “ff”, “mf” and “mm” denote the  $NN$  free elastic plus  $NN$  free inelastic scattering cross sections, modified  $NN$  reduced elastic plus  $NN$  free inelastic scattering cross sections and modified  $NN$  reduced elastic plus modified  $NN$  reduced inelastic scattering cross sections, respectively.

To study the effects of both  $NN$  elastic and inelastic scattering cross sections on  $\pi^-/\pi^+$ , We first studied their effects on  $\Delta(1232)$  and pion productions. We ignore  $N^*$  production here, because it is mainly related to more energetic collisions. Shown in Fig. 3 is the evolution of pion and  $\Delta(1232)$  multiplicities in the reaction of  $^{48}\text{Ca}+^{48}\text{Ca}$  at a beam energy of 400 MeV/nucleon. The “ff”, “mf” and “mm” denote the  $NN$  free elastic plus  $NN$  free inelastic scattering cross sections (i.e., full free  $NN$  scattering cross sections), modified  $NN$  reduced elastic plus  $NN$  free inelastic scattering cross sections and modified  $NN$  reduced elastic plus modified  $NN$  reduced inelastic scattering cross sections (i.e., full modified  $NN$  reduced scattering cross sections), respectively. First, we can see that  $\Delta(1232)$  production is mainly at the com-

pression stage. Compared with the full free  $NN$  scattering cross-sections case, both the modified  $NN$  reduced elastic and the modified  $NN$  reduced inelastic scattering cross sections cause more  $\Delta(1232)$  resonance production. This is because for the “mf” case, the modified  $NN$  reduced elastic scattering cross section causes the colliding nuclei to show less stopping [41, 46, 52]; as a result more energetic  $NN$  collisions in fireball matter produce more resonances. For the “mm” case, the reduction factor  $R_{medium}$  of the  $NN$  inelastic scattering cross section not only makes the colliding nuclei further less stopping but also makes resonance less absorptive (i.e., the cross section of  $NN \rightarrow NN$  decreases). Effects of the preceding two factors are larger than that of the modified  $NN$  reduced inelastic cross section. Therefore, number of resonances also relatively increase. More resonances produce more  $\pi^-$ 's and  $\pi^+$ 's. We thus see more  $\pi^-$ 's and  $\pi^+$ 's for the “mm” case than for the “mf” case and than for the “ff” case. Second, one can see that  $\pi^-$  production is more sensitive to  $NN$  scattering cross sections than  $\pi^+$ . It is known that  $nn$  collisions mainly produce  $\pi^-$ ,  $pp$  collisions mainly produce  $\pi^+$  and  $np$  collisions produce roughly equal numbers of  $\pi^-$  and  $\pi^+$  [36]. Although the modified  $NN$  reduced cross section makes the colliding nuclei less stopping, relative to  $nn$  collisions, the Coulomb force between proton and proton almost cancel out the effect of a largely modified  $pp$  reduced cross section (shown in Fig. 2). Therefore  $\pi^-$  production is more sensitive to the  $NN$  elastic and inelastic scattering cross sections than  $\pi^+$ . Finally, we can clearly see that more  $\pi^-$ 's are produced than  $\pi^+$ 's. This is understandable for neutron-rich  $^{48}\text{Ca}+^{48}\text{Ca}$  collision, in which there are more  $nn$  collisions than  $pp$  collisions [53].

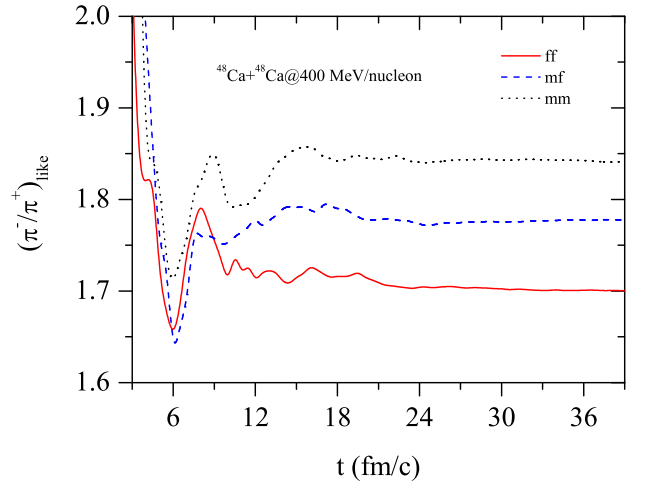


FIG. 4: Effects of both elastic and inelastic  $NN$  scattering cross sections on  $(\pi^-/\pi^+)_{like}$  as a function of time in the reaction of  $^{48}\text{Ca}+^{48}\text{Ca}$  at a beam energy of 400 MeV/nucleon.

To reduce the systematic errors in simulations, especially in experimental analysis, one usually studies the

$\pi^-/\pi^+$  [4, 5, 53] instead of  $\pi^-$  or  $\pi^+$  only. Shown in Fig. 4 are effects of elastic and inelastic  $NN$  scattering cross sections on the  $(\pi^-/\pi^+)_{like}$  as a function of time in the central reaction of  $^{48}\text{Ca}+^{48}\text{Ca}$  at a beam energy of 400 MeV/nucleon. In the dynamics of pion resonance productions and decays the  $(\pi^-/\pi^+)_{like}$  reads [53]

$$(\pi^-/\pi^+)_{like} \equiv \frac{\pi^- + \Delta^- + \frac{1}{3}\Delta^0}{\pi^+ + \Delta^{++} + \frac{1}{3}\Delta^+}. \quad (5)$$

This ratio naturally becomes the  $\pi^-/\pi^+$  ratio at the freeze-out stage [53]. From Fig. 4 we can first see that, owing to the abundant neutron-neutron scatterings when the two neutron skins start overlapping at the beginning of the reaction, the  $(\pi^-/\pi^+)_{like}$  ratio reaches a very high value in the early stage of the reaction. The sensitivity of  $(\pi^-/\pi^+)_{like}$  to the effects of both elastic and inelastic  $NN$  scattering cross sections is clearly shown after  $t = 15 fm/c$ . We can see that the  $\pi^-/\pi^+$  value using full free  $NN$  scattering cross sections is smaller than that of using modified  $NN$  reduced elastic scattering cross section. The  $\pi^-/\pi^+$  value using modified  $NN$  reduced elastic scattering cross section is also smaller than that of using full modified  $NN$  reduced scattering cross sections. This is understandable from the preceding charged-pion production analysis shown in Fig. 3. We also did a calculation for central Au+Au reaction at 400 MeV/nucleon and found that compared with the “mf” case used in Ref. [1], with the “mm” case the  $\pi^-/\pi^+$  ratio increases

about 7% while the charged-pion multiplicity increases about 30%. Hence the effects of  $NN$  elastic and inelastic scattering cross sections play an important role in studying the high-density behavior of nuclear symmetry energy by using  $\pi^-/\pi^+$  in *neutron-rich* heavy-ion collisions.

In conclusion, in the framework of the isospin-dependent transport model IBUU and the scaling model according to nucleon effective mass, we studied the effects of elastic and inelastic  $NN$  scattering cross sections on  $\pi^-/\pi^+$  in the neutron-rich reaction of  $^{48}\text{Ca}+^{48}\text{Ca}$  at a beam energy of 400 MeV/nucleon. We find that both  $NN$  elastic and inelastic scattering cross sections in neutron-rich heavy-ion collisions affect  $\Delta_{1232}$ ,  $\pi^-$  and  $\pi^+$  production, as well as the value of  $\pi^-/\pi^+$ . The reduced  $NN$  elastic and inelastic cross sections increase the number of  $\pi^-$  more evidently than  $\pi^+$ . The value of  $\pi^-/\pi^+$  thus also increases accordingly. It is expected that the choice adopted for the  $NN$  cross section affects significantly also the amount of pre-equilibrium nucleon emission and the corresponding  $N/Z$  ratio, which is also an observable widely investigated in heavy-ion reactions, from both the experimental and the theoretical point of view. Such an observable also needs to be carefully investigated, in parallel with meson production, before reaching any conclusion about the cross sections and the behavior of the symmetry energy at high densities.

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